

Temperature-Dependent Electrical Conductivity of GeTe-Based RF Switches

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Abstract: *The DC and RF electrical behavior of GeTe-based RF switches was characterized in both ON and OFF states at temperatures ranging from 25 K to 375 K. ON-state current-voltage characteristics vary only weakly with temperature, exhibiting Ohmic behavior at all temperatures across the full voltage range measured. OFF-state current varies linearly with voltage at all measured fields for low temperatures, but transitions to super-linear behavior at higher fields and temperatures. Unlike the ON-state case, the low-field OFF-state DC conductance exhibits considerable temperature dependence, decreasing four orders of magnitude as the temperature is decreased from 375 K to 200 K, resulting in dramatically increased OFF/ON resistance ratios at low temperatures. RF performance, evaluated through small signal S-parameter measurements, exhibits minimal temperature variation in either the ON or OFF states.*

Keywords: RF switch; GeTe; phase change material; temperature dependence

Introduction

In order to counter increasingly sophisticated electronic threats, future military RF electronic systems must demonstrate significant reconfigurability, supporting operation across multiple frequency bands and operational modes. To achieve this functionality, many emerging system concepts employ networks of switched subsystems, allowing real-time or quasi-real-time system adaptation to the specific RF environment and task. Such systems rely heavily on the integration of high-performance RF switches to enable reconfigurability. The ideal RF switch for this application must demonstrate extremely low insertion loss and high isolation across a broad frequency range, high linearity and dynamic range, fast switching times, low power consumption, high power handling, and excellent reliability. Among the most promising candidates for these switches are phase change material (PCM) devices based on the binary chalcogenide GeTe, which can be reversibly and non-volatilely switched between an electrically insulating amorphous phase and an electrically conductive polycrystalline phase. Initial GeTe-based RF switches have shown very low insertion loss and sufficient isolation over a broadband, switching times less than 100 ns, and zero stand-by power consumption[1-4]. While there exist numerous studies of DC conduction in general PCM chalcogenides[5-8], few investigations of the electronic behavior of GeTe at very low temperatures have been

published, nor have investigations of PCM device RF performance at temperatures other than ~300 K been reported. In this work, we evaluate the temperature-dependence of the DC and RF electrical behavior of GeTe-based RF switches in ON (polycrystalline) and OFF (amorphous) states from cryogenic to elevated temperatures. By examining the temperature dependence of the ON and OFF state conduction, we gain a greater understanding of the underlying electronic transport mechanisms within the GeTe, offering insight into the device's RF behavior and opening pathways for performance improvement.

Experimental Method

Series-configuration, indirectly-heated GeTe-based RF switches were fabricated as described in [2]. The basic four-terminal switch structure, depicted in the schematic of Figure 1, consists of a two-terminal Ti/Pt/Au coplanar waveguide with a portion of the signal line replaced by a thin active GeTe layer deposited via DC Magnetron sputtering[9]. Below the active layer lies a buried thin film heater, electrically isolated from the GeTe through a thin SiN barrier layer. The GeTe can be non-volatilely switched between polycrystalline and amorphous phases by electrically pulsing the thin film heater through independently controlled terminals. Short, high temperature pulses result in a melt-quench cycle, amorphizing the GeTe and leaving the switch in the electrically insulating OFF state. Longer, lower temperature pulses result in the recrystallization of the GeTe, leaving the switch in the electrically conductive ON state. The volume of GeTe actuated during each switching cycle is approximately defined by the GeTe film thickness (~85 nm), the switch signal linewidth (20 μm to 30 μm in the devices measured) and the thin film heater width (1.3 μm to 2.5 μm in the devices measured).

Prior to sample temperature ramping, switches were toggled at room temperature, demonstrating OFF/ON resistance ratios, $R_{\text{OFF}}/R_{\text{ON}}$, of $\sim 10^4$ - 10^5 . The DC electrical behavior of the GeTe switches was evaluated by switching the device into the ON state and recording current-voltage (I-V) characteristics at temperatures ranging from 25 K to 375 K in 25 K increments. The device was then returned to room temperature, switched into the OFF-state, and the variable-temperature measurements repeated. The maximum DC voltage applied across the RF terminals was limited to 1 V (ON state) and 8 V (OFF state) to avoid self-

switching due to current-induced Joule heating of the GeTe. S-parameter measurements at frequencies from 10 MHz to 40 GHz were also collected for each state at each temperature. SOLT calibration was performed on an in-situ CS-5 standard, with the calibration verified at multiple temperatures. All measurements were taken with the devices under vacuum ($< 1 \times 10^{-6}$ Torr).

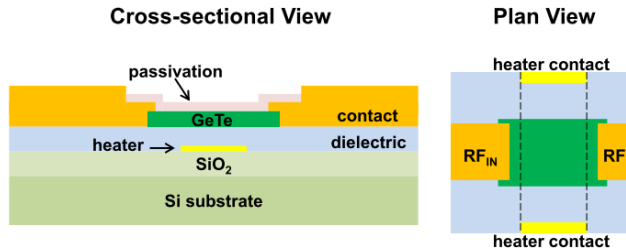


Figure 1. Cross-sectional and plan view schematics of a GeTe-based PCM RF Switch

Results and Discussion

Temperature-dependent DC I-V curves measured on a switch toggled to the ON state are plotted on a linear scale in Figure 2(a). The device exhibits linear I-V behavior across the full 1 V applied bias range, with a maximum conductance, dI/dV , of 0.053 S measured at 25 K. The DC conductance varies only weakly with temperature, decreasing $\sim 7\%$ as the temperature is raised to 375 K. The weak temperature dependence and decrease in conductance with increasing temperature observed for the ON state device is consistent with the degenerate semiconductor model often used to describe conduction in crystalline chalcogenides[6]. Room temperature Hall measurements on similar polycrystalline GeTe films indicate the material is p-type, with a carrier density of $\sim 8 \times 10^{20} \text{ cm}^{-3}$ and a mobility of $\sim 10 \text{ cm}^2/\text{Vs}$.

Unlike the ON-state case, DC conduction in the OFF state varies substantially with temperature. I-V traces measured on the same device switched into the OFF state are plotted on a log-log scale in Figure 2(b), with the inset depicting the same data on a linear scale. At all temperatures, I-V characteristics are linear at low-fields; for the lowest temperatures, $T \leq 100 \text{ K}$, this linearity extends through the entire 8 V measured bias range. However, as the temperature is raised above 100 K, the current gradually assumes a super-linear dependence on voltage as the electric field across the GeTe is increased. The transition voltage appears to vary with temperature, but is estimated to be 1-2 V, corresponding to an approximate electric field of 5-10 kV/cm across the GeTe, consistent with previous reports on amorphous chalcogenide conduction[5]. This high-field super-linearity has been cited as a key source of PCM switch non-linearity[10]; as a result, the non-linear

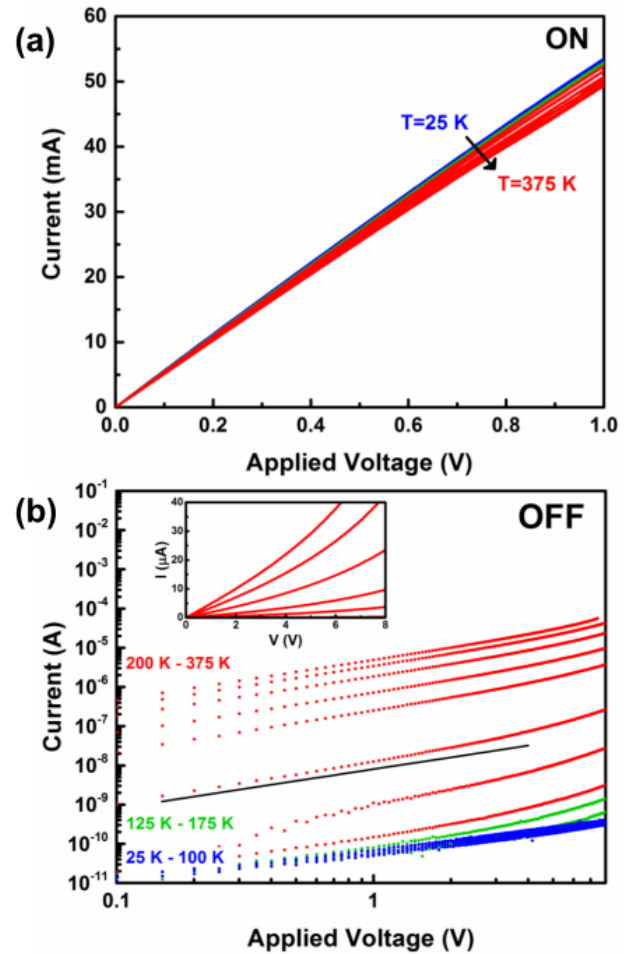


Figure 2. I-V characteristics measured at temperatures from 25 K to 375 K on a single switch in both the (a) ON and (b) OFF states. Inset in (b) is OFF- state data plotted on a linear scale. The solid black line in (b) is a linear I-V guide for the eye. Measurements acquired at 25 -100 K, 125 – 175 K, and 200 – 375 K are plotted in blue, green, and red, respectively.

performance of GeTe-based RF switches may possibly improve when operated at temperatures less than 100 K, where conduction appears to be Ohmic across a much larger electric field range.

In the linear low-field regime, the OFF-state DC conductance is effectively constant for temperatures less than 200 K. However, as shown in Figure 3(a), the low-field conductance increases nearly four orders of magnitude as the temperature is raised from 200 K to 375 K. Two distinct activation energies can be identified. For 275 K - 375 K, we extract $E_A \sim 0.27 \text{ eV}$, consistent with measurements that place the room temperature Fermi level in amorphous GeTe $\sim 0.3 \text{ eV}$ above the valence band edge[8]. For 200 K - 275 K, we observe a steeper slope and correspondingly larger activation energy of $E_A \sim 0.53 \text{ eV}$, suggesting that low temperature conduction in the

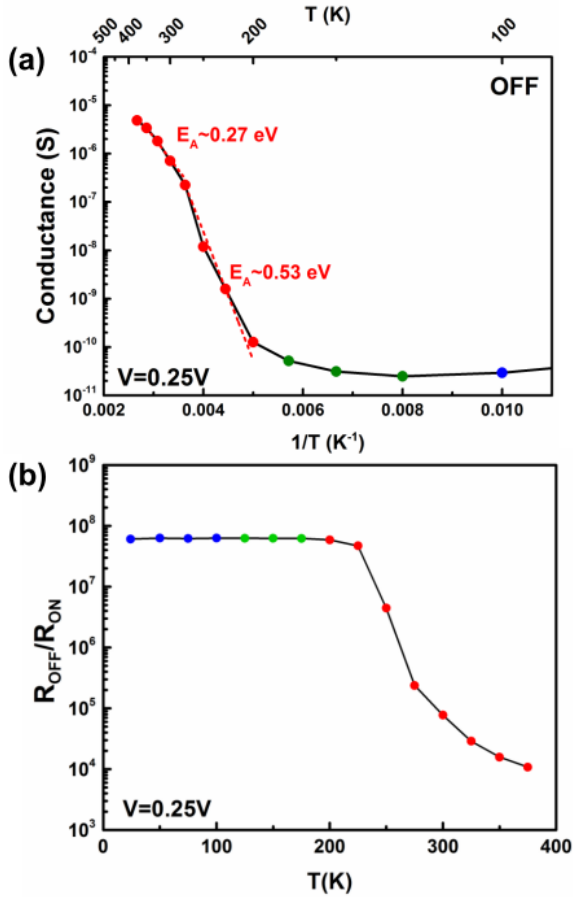


Figure 3. (a) Low-field DC conductance vs. temperature for the OFF-state switch. (b) DC resistance ratio, R_{OFF}/R_{ON} , vs. temperature. All measurements were acquired at 0.25 V applied bias.

amorphous GeTe device may be due to a different mechanism than room temperature conduction.

The difference in temperature trends between the ON and OFF states results in a dramatic increase in R_{OFF}/R_{ON} at low temperatures, depicted in Figure 3(b), with R_{OFF}/R_{ON} reaching $\sim 10^8$ for $T < 200$ K. The good thermal coupling between the thin film heater and the active GeTe layer enables switching at cryogenic temperatures with only moderate increases in required heater power. This is shown in Figure 4, where a separate device is cycled more than 500 times while held at 10 K. The measured OFF/ON ratio for this device at low temperature is greater than 10^9 .

While DC measurements provide insight into fundamental device operation and material capabilities, the RF switch performance ultimately must be assessed using high-frequency techniques. S_{21} and S_{11} measurements acquired on the switch in both ON and OFF states at temperatures from 25 K to 375 K and frequencies 10 MHz to 40 GHz are plotted in Figure 5. As a result of device symmetry, S_{22} is nearly identical to S_{11} and thus is not plotted here. With no de-embedding, the ON-state S_{21} is approximately -1.3 dB at low frequencies, decreasing to -2.4 dB at 40 GHz,

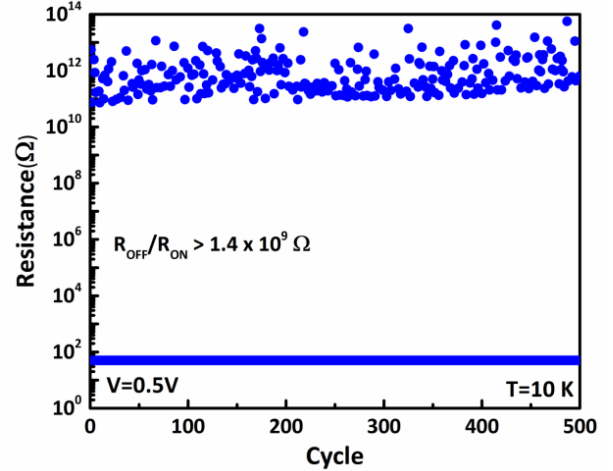


Figure 4. DC resistance measured on a switch cycled between ON and OFF states at 10 K. The measured OFF/ON resistance ratio exceeds 10^9 .

indicating low ON-state insertion loss across the entire measured frequency range. S_{21} varies slightly with temperature, with the greatest change observed at frequencies greater than 1 GHz, where the S_{21} decreases by ~ 0.3 dB as T is increased from 25 K to 175 K, then increases by approximately the same amount as the temperature is further increased to 375 K. ON-state S_{11} shows a similar temperature trend, with slightly larger parameter variation at high frequencies: S_{21} decreases by ~ 1 dB as T is increased from 25 K to 175 K, then increases by ~ 5 dB as T is raised to 375 K. The generally minimal variation in ON-state S-parameters is consistent with the observed DC behavior, where low-field conductance was shown to vary only weakly with temperature.

OFF-state S-parameters also exhibit slight temperature variation, with an inflection point of ~ 175 -200 K, the same temperature at which DC conduction begins to shift dramatically (Figure 3) and trend-reversal is observed in the ON-state. OFF-state S_{11} mimics the ON-state behavior, initially decreasing by ~ 0.2 dB, then increasing by ~ 0.4 dB. OFF-state S_{21} exhibits the reverse trend: S_{21} initially increases by ~ 0.4 , then decreases by ~ 2 dB, with maximum temperature variation observed at frequencies less than 6 GHz. Given the large change in DC resistance in the OFF-state, the relatively minimal temperature dependence of the S-parameters suggest that the OFF-state RF performance is dominated by parasitic capacitive effects determined by device geometry, which are largely independent of operating temperature.

Summary

The electrical behavior of GeTe-based RF PCM switches was evaluated at temperatures ranging from 25 K to 375 K in both ON and OFF states. ON-state device performance varies little with temperature in either DC or RF regimes. OFF-state small signal S-parameters also exhibit minimal

temperature-dependence, while OFF-state DC electrical behavior varies dramatically with temperature. Low-field DC conductance decreases by approximately four orders of magnitude as the temperature is decreased from 375 K to 200 K, resulting in OFF/ON resistance ratios that can exceed 10^9 at cryogenic temperatures. Furthermore, while the OFF-state DC current exhibits a super-linear dependence on voltage for higher fields and temperatures, at 100 K and below, the DC OFF-state current appears linear across the full 8 V measured voltage range. The unique OFF-state behavior of the GeTe device at cryogenic temperatures suggests the utility of low-temperature operation for applications that require switching with extremely high OFF/ON ratios and/or high linearity. Further study is required to fully understand the observed DC and RF behaviors in order to optimize PCM switch performance for reconfigurable RF applications.

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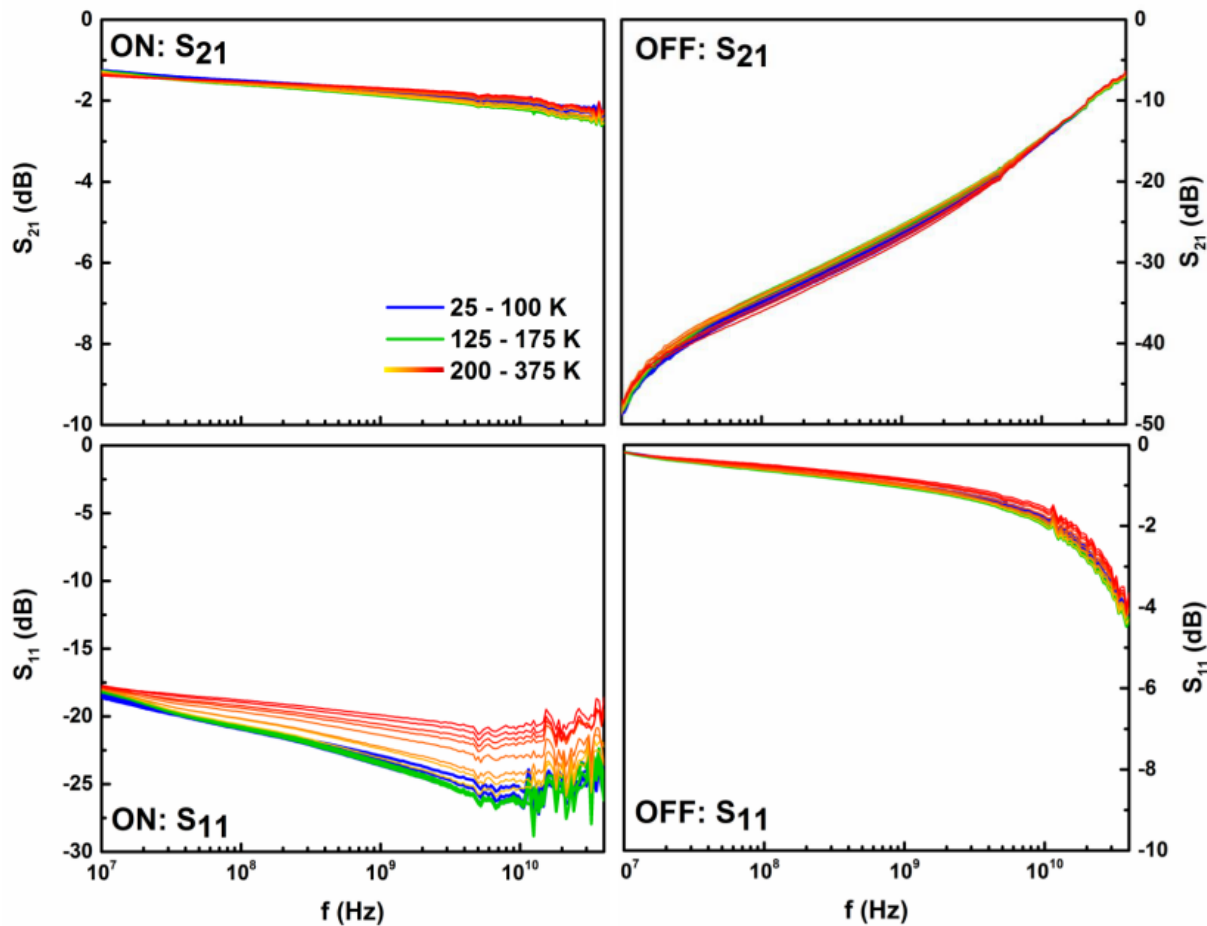


Figure 5. S-parameter measurements acquired on a single switch in both the ON and OFF states at temperatures ranging from 25 K to 375 K